

Review

Progress in Photonic Crystals for Ionizing Radiation Dosimetry

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Abstract: With the expanding applications of nuclear technology across various fields, radiation dosimeters have become indispensable tools. Traditional dosimeters face limitations including complex readout procedures and environmental susceptibility. Responsive photonic crystals, a class of structural color materials with unique periodic structures and optical properties, demonstrate significant potential for ionizing radiation detection. This review provides an overview of the radiation response mechanisms of photonic crystals and highlights recent research progress in constructing photonic crystal dosimeters based on radiation-induced degradation, crosslinking, monomer polymerization, 3D printing and refractive index change. Future research directions and potential applications are discussed.

Keywords: radiation chemistry; photonic crystals; radiation dosimetry; radiation effect; polymer

1. Introduction

Radiation dosimeters play an essential role in diverse applications including aerospace, radiation medicine, large-scale scientific facilities, and radiation processing [1–8]. As related industries advance, new requirements and challenges have emerged for dosimeter technologies. For example, in aerospace and deep-space exploration, dosimeters should ideally be passive (requiring no external bias voltage), lightweight, capable of real-time display, and responsive to multiple types of space radiation to ensure astronaut and equipment safety while minimizing fuel consumption. In radiation therapy—including conventional radiotherapy [9,10] and emerging heavy-ion therapy [11]—precise measurement of absorbed dose and its spatial distribution in tissues and organs is critical [12–14]. This necessitates dosimeters with high accuracy, sensitivity, and superior spatial resolution to enable targeted tumor destruction while sparing healthy tissues. For large-scale scientific facilities such as synchrotron radiation sources, neutron scattering platforms, and laser fusion facilities, accurate measurement of beam profile and collimation is essential for operational performance, creating an urgent need for spatial mapping of radiation fields. Furthermore, as radiation technology expands into material modification and processing [15–18], dosimeters face new challenges in portability, online monitoring, and broad-range dose response. Traditional dosimeters are increasingly unable to meet these evolving requirements, driving the development of novel dosimeters with real-time capabilities, wide dose-response ranges, and high spatial resolution.

Photonic crystals (PCs) are periodic dielectric structures characterized by photonic bandgaps, allowing precise control over light propagation. Responsive photonic crystals—a class of structural color materials—undergo significant color changes under external stimuli such as temperature, chemical environment, light, or electromagnetic fields. By using ionizing radiation as an external stimulus and correlating the spectral changes of



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PCs with absorbed dose, real-time visual detection of ionizing radiation becomes feasible. Recent research on radiation chemistry in structural color materials has focused primarily on radiation effects in polymer-based photonic crystals. This review highlights progress in constructing photonic crystal dosimeters based on radiation-induced degradation, crosslinking, monomer polymerization and refractive index change, and explores 3D printing strategies for photonic crystal dosimeters, as shown in Figure 1.

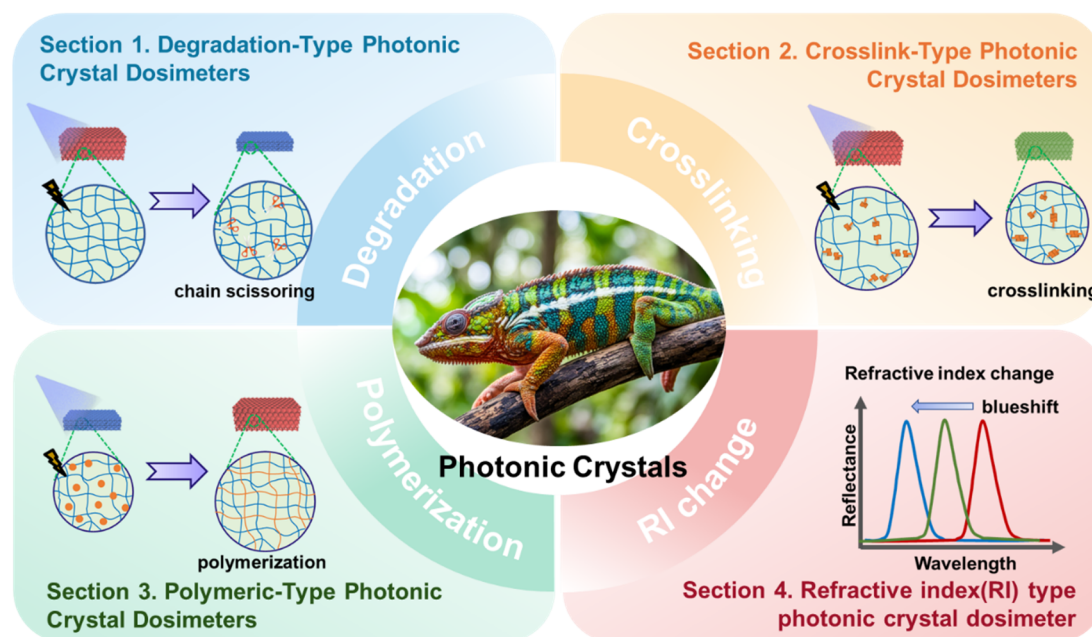


Figure 1. Classification of photonic crystal dosimeters.

2. Radiation Effects in Polymers

Upon exposure to ionizing radiation (e.g., γ -rays, X-rays, electron beams), polymers and their monomeric precursors undergo significant physical and chemical changes, collectively referred to as radiation effects. These effects arise from the interaction of high-energy photons or charged particles with the polymer chains, leading to the formation of excited states, ions, and free radicals. The subsequent chemical transformations can fundamentally alter the material's molecular structure, mechanical properties, and optical characteristics. The primary manifestations include radiation-induced degradation, crosslinking, and polymerization (Figure 2). Understanding these radiation-induced processes is crucial for designing responsive materials such as photonic crystal dosimeters, where controlled structural changes are harnessed for radiation detection [19].

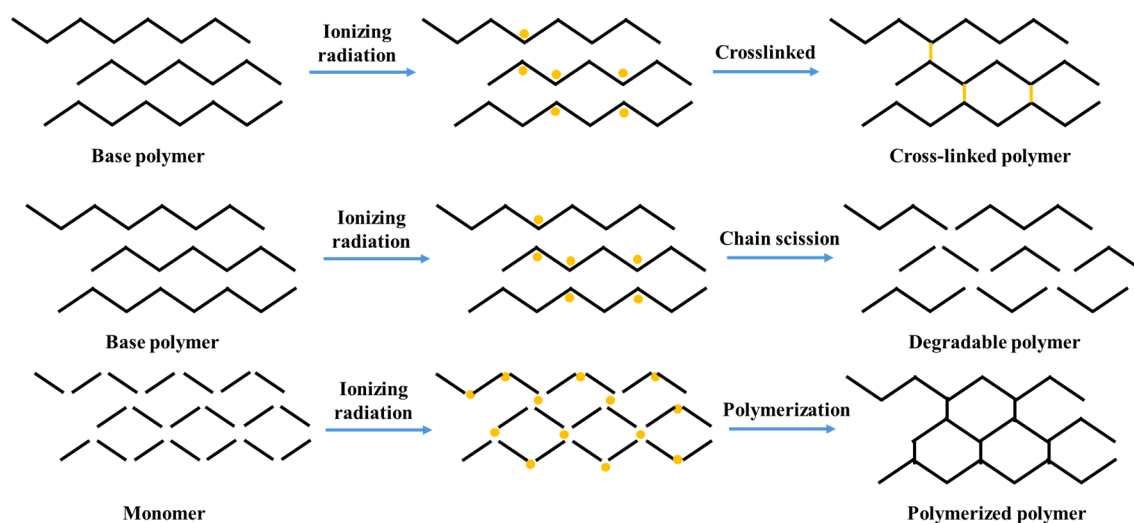


Figure 2. Schematic diagram of chemical reactions induced by high-energy radiation in polymers.

2.1. Radiation-Induced Degradation

Radiation-induced degradation refers to main-chain scission of polymers under ionizing radiation, leading to a reduction in molecular weight with increasing absorbed dose and potentially forming monomeric fragments, thereby altering mechanical and physicochemical properties. This process is particularly pronounced in polymers with weak backbone bonds or quaternary carbon atoms, such as poly(methyl methacrylate) (PMMA), polytetrafluoroethylene (PTFE), and polyisobutylene. Degradation is especially significant at high doses or in radiation-sensitive materials, and it often results in reduced tensile strength, increased surface roughness, and loss of optical clarity.

The extent and rate of radiation degradation are governed by several factors, including irradiation atmosphere, dose rate [20–22], temperature [23–25], and the presence of additives [26–28]. Oxygen is known to promote degradation significantly. For example, polytetrafluoroethylene (PTFE) exhibits a degradation yield of 0.19 $\mu\text{mol/J}$ when irradiated in air, compared to only 0.01–0.02 $\mu\text{mol/J}$ under vacuum. This enhancement is attributed to the participation of oxygen in radical reactions during irradiation: radiation-generated radicals react with molecular oxygen to form peroxy radicals, which subsequently attack the polymer backbone, initiating chain reactions that accelerate degradation. The oxygen-mediated degradation mechanism is detailed in (Equation (1) to Equation (10)) [29].



These equations illustrate a free-radical chain mechanism. Initially, radiolysis produces alkyl radicals ($\text{R}^\bullet$) and hydrogen atoms (Equation (1)). In the presence of oxygen, peroxy radicals ($\text{ROO}^\bullet$) form rapidly (Equation (2)), which then abstract hydrogen from adjacent chains to generate hydroperoxides (ROOH) and new alkyl radicals (Equation (3)). Hydroperoxides are thermally unstable and decompose into alkoxy radicals ($\text{RO}^\bullet$) and hydroxyl radicals ($\cdot\text{OH}$) (Equation (4)), both of which can further abstract hydrogen (Equations (5) and (6)). The alkoxy radical can undergo β -scission, leading to direct chain scission (Equation (7)). Termination occurs via radical recombination (Equations (8) and (9)), while hydroperoxides may also decompose non-radically (Equation (10)). This cascade results in a dramatic reduction in molecular weight even at modest absorbed doses.

Elevated temperatures enhance chain mobility, reducing the probability of radical recombination within the solvent cage and thus accelerating degradation. At equivalent absorbed doses, higher dose rates tend to result in lower degradation yields due to increased radical-radical recombination. Additives containing aromatic rings (e.g., benzene rings) can act as radical scavengers, improving radiation stability [30]. For instance, incorporating 1% by weight of an aromatic antioxidant can reduce the degradation rate of polypropylene by more than 50%. In contrast, pro-oxidant additives containing transition metals (e.g., cobalt or manganese stearate) can sensitize degradation, making polymers more susceptible to radiolytic chain scission. Understanding these factors allows for the rational design of degradation-type photonic crystal dosimeters, where controlled backbone cleavage leads to predictable shifts in structural color.

2.2. Radiation Crosslinking Effects in Polymers

Radiation crosslinking refers to the formation of covalent bonds between polymer chains upon exposure to ionizing radiation, resulting in a three-dimensional network structure [31]. The crosslinking reaction process is as

shown in Equation (11) to (13). Crosslinking typically occurs at relatively low doses, especially in polymers containing radiation-sensitive groups such as unsaturated bonds. Crosslinking density is proportional to absorbed dose within a certain range.



Similar to degradation, crosslinking is influenced by multiple factors, including irradiation temperature [32], dose rate [33], atmosphere [34], and the presence of additives. The process is governed by the recombination of polymer chain radicals, with crosslinking efficiency closely related to chain mobility. Temperature enhances molecular motion, promoting crosslinking by increasing the probability that two radical sites on different chains will encounter each other before undergoing side reactions. For example, crosslinking of low-density polyethylene increases nearly threefold when the irradiation temperature is raised from 25 °C to 150 °C. Oxygen inhibits crosslinking by reacting with free radicals to form peroxy radicals, which are less likely to recombine into crosslinks and instead may lead to degradation. Therefore, crosslinking reactions are typically carried out under inert atmospheres (e.g., nitrogen or vacuum) or in the presence of radical scavengers to minimize competing oxidative degradation.

Additives containing unsaturated bonds can sensitize crosslinking, significantly reducing the required dose, as the cleavage of double bonds demands less energy than typical crosslinking pathways. Common crosslinking sensitizers include triallyl cyanurate (TAC), trimethylolpropane triacrylate (TMPTA), and other multifunctional monomers. These molecules act as “bridging” agents: upon radiolysis, they generate reactive radicals that can link two polymer chains together more efficiently than direct chain–chain recombination. The use of such sensitizers can reduce the required crosslinking dose by an order of magnitude, from several hundred kGy to tens of kGy. In addition, the presence of fillers such as carbon black or silica can influence crosslinking by altering chain mobility or by acting as radical sinks. Understanding these factors is essential for designing crosslink-type photonic crystal dosimeters, where radiation-induced network formation causes volume shrinkage or refractive index changes that modulate the photonic bandgap.

2.3. Radiation-Induced Monomer Polymerization

Radiation-induced monomer polymerization utilizes ionizing radiation to initiate the polymerization of monomers into polymers, typically proceeding efficiently even at low radiation doses. Unlike thermal or photoinitiated polymerization, radiation polymerization does not require added initiators, as the radiation itself generates reactive species directly from the monomer or from the solvent/medium. This “initiator-free” characteristic makes it particularly attractive for biomedical and high-purity applications. Most radiation polymerizations proceed via a radical mechanism, although ionic polymerization can occur under specific conditions (e.g., in very dry systems or at low temperatures). In the radical pathway, monomer molecules (M) absorb radiation energy to generate reactive radicals (R[•]), which initiate chain propagation. Propagation continues until termination occurs through radical recombination or disproportionation. The overall process encompasses three stages: initiation (Equation (14)), propagation (Equations (15) to (17)), and termination (Equations (18) and (19)).



The initiation step (Equation (14)) involves the radiolysis of monomer molecules to form two radicals (often via homolytic cleavage of a double bond or C–H bond). The rate of initiation is directly proportional to the dose rate and the monomer’s radiation chemical yield (G-value). In the propagation steps (Equations (15) to (17)), the

growing chain radical adds successive monomer units. Termination occurs either by combination (Equation (18)), yielding a single polymer chain with double the molecular weight, or by disproportionation (Equation (19)), producing two polymer chains with terminal unsaturation. The balance between combination and disproportionation depends on monomer structure and reaction conditions.

Radiation polymerization is influenced by several key parameters, including temperature [35], dose rate [36], atmosphere [37], and the presence of additives. While polymerization can proceed at low temperatures (even cryogenically, leading to living-like polymerization in some systems), elevated temperatures markedly accelerate molecular motion and thus increase the polymerization rate. Monomer conversion typically increases with absorbed dose, demonstrating a positive correlation; however, at very high doses, the rate may plateau due to monomer depletion or increased viscosity that limits diffusion. Oxygen serves as an effective radical scavenger, thereby inhibiting polymerization; even trace amounts of dissolved oxygen can significantly extend the induction period. Therefore, radiation polymerization is often conducted under inert gas purging (e.g., nitrogen or argon) to remove oxygen. In contrast, multifunctional crosslinkers—particularly those containing double bonds—can sensitize the polymerization process, reducing the required dose and improving overall efficiency. These crosslinkers, such as ethylene glycol dimethacrylate (EGDMA) or divinylbenzene, also lead to the formation of crosslinked polymer networks rather than linear chains, which can be advantageous for fabricating mechanically robust hydrogels or photonic crystal matrices. Additionally, the presence of chain transfer agents (e.g., thiols) can be used to control molecular weight and introduce functional end-groups, expanding the versatility of radiation-induced polymerization for tailored material design. This polymerization mechanism forms the basis for polymeric-type photonic crystal dosimeters, where radiation-induced monomer conversion leads to volume expansion or refractive index changes that are quantitatively correlated with absorbed dose.

3. Preparation and Response Principles of Photonic Crystals

Although the concept of photonic crystals was independently introduced in 1987 by Yablonovitch and Sajeev John [38], such structures have long existed in nature—for example, the iridescent colors of butterfly wings, beetle shells, and bird feathers arise from photonic crystal architectures and are known as structural colors [39,40]. Opal is another natural photonic crystal, its distinctive coloration originating from the close-packed arrangement of amorphous silica colloidal spheres.

3.1. Self-Assembly of Photonic Crystals

Artificial photonic crystals can be fabricated via top-down or bottom-up approaches. The top-down approach relies on conventional microprocessing techniques, such as laser lithography, electron-beam etching, and vapor deposition [41,42]. Drawing on semiconductor design and fabrication processes, researchers have successfully constructed three-dimensional photonic crystals, including layered “woodpile” structures [43,44]. While this method yields structures with low defect density and high periodicity, it requires expensive equipment, involves complex procedures, and is not well-suited for large-scale production.

In contrast, the bottom-up approach builds periodic structures through the ordered assembly of building blocks—for example, submicron silica or polystyrene microspheres, or block copolymers. Key strategies include gravity- or inertia-driven self-assembly and capillary force-induced assembly. These techniques are operationally simple, cost-effective, and readily adaptable to large-scale industrial applications [45–47].

3.1.1. Gravity- or Inertia-Driven Self-Assembly

This method is based on the spontaneous sedimentation of colloidal particles under the influence of gravity, leading to the formation of ordered structures. Despite its operational simplicity, the resulting photonic crystals often exhibit notable defects, limited structural periodicity, and slow assembly kinetics. Gravity-driven assembly involves the interplay of multiple forces—including diffusion, Brownian motion, and electrostatic interactions—necessitating precise control over the density, size distribution, and dispersion of the colloidal microspheres. To enhance assembly efficiency, researchers have introduced external forces such as centrifugal fields or vacuum filtration to accelerate sedimentation [48]. This approach is particularly effective for assembling nanoparticles into photonic crystals with bandgaps in the short-wavelength region [49].

3.1.2. Capillary Force-Induced Self-Assembly

Originating from surface tension, capillary forces operate over micron-to-millimeter length scales and play a critical role in driving the ordered assembly of colloidal nanoparticles. By precisely controlling the evaporation

dynamics of colloidal emulsions, capillary forces at the gas–liquid interface can direct the assembly of microspheres into highly ordered structures. A classic example is the vertical deposition self-assembly method (Figure 3), in which solvent evaporation from curved menisci facilitates the organized deposition of colloidal particles onto vertical substrates [50,51]. Compared to gravity sedimentation, vertical deposition offers more precise control over evaporation kinetics, yielding high-quality photonic crystals with high crystallinity and close-packed structures. Its combination of operational simplicity, high efficiency, and tunable processing parameters has established it as the predominant method for fabricating colloidal photonic crystals.

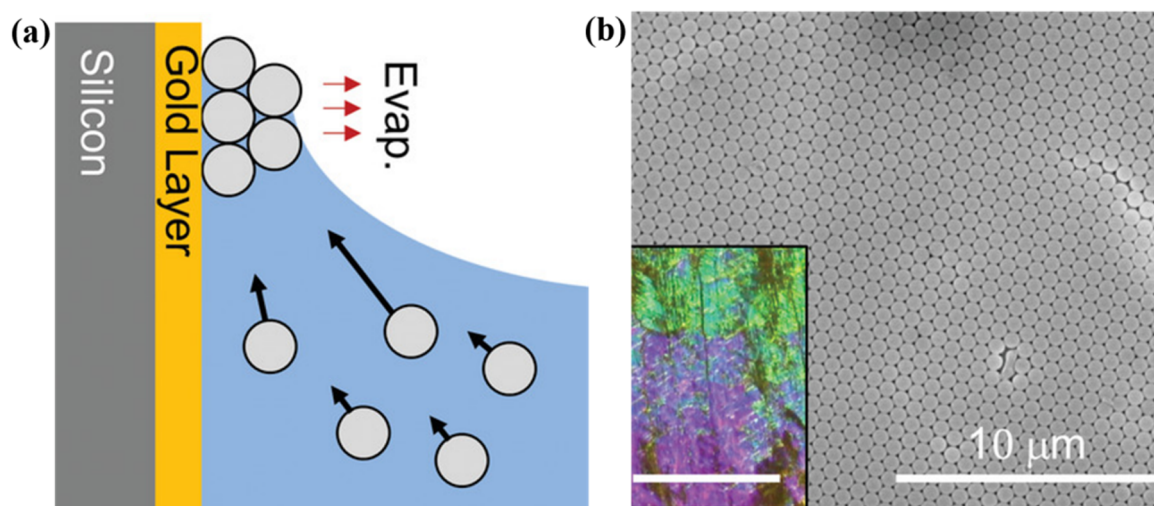


Figure 3. Vertical deposition self-assembly of photonic crystals: (a) Schematic; (b) SEM image of self-assembled photonic crystals and optical diffraction pattern (inset). Reprinted/adapted with permission from Ref. [52]. Copyright 2019, John Wiley and Sons.

3.2. 3D Printing of Photonic Crystals

As an additive manufacturing technology, 3D printing enables the rapid, high-resolution fabrication of customized three-dimensional structures without the need for molds or post-processing. It has found extensive applications in biomedicine, aerospace, and the automotive industry [53]. The use of 3D printing in the fabrication of photonic crystals presents a promising route for advancing structural color materials in fields such as optics, communications, and biophotonics [54].

Among the various techniques, photopolymerization-based 3D printing—particularly Two-Photon Lithography (TPL) and Digital Light Processing (DLP)—is among the earliest and most mature approaches, known for its high speed, precision, and smooth surface finish [55]. Two-Photon Lithography (TPL) is a high-resolution micro/nanofabrication technique that utilizes pulsed lasers to induce localized photochemical reactions within materials, enabling precise three-dimensional positioning for high-precision structural color applications [56–61]. Although TPL excels in material penetration and spatial selectivity, it faces challenges in achieving large-scale, efficient printing.

Digital Light Processing (DLP), in contrast, projects UV patterns to polymerize precursors layer by layer into three-dimensional structures [62]. Precursors containing colloidal particles have been employed to fabricate photonic crystal films, and their integration with DLP enables the layer-by-layer construction of 3D structures.

Yanlin Song [63,64] utilized hydrogen bond-assisted colloidal resins combined with a droplet-based 3D printing strategy to produce well-assembled three-dimensional structural color materials (Figure 4). In their photopolymerization system, polystyrene colloidal particles and monomers are stabilized by hydrogen bonds during the printing process. Continuous curing generates a pressure differential between the freshly filled resin and the cured layers, creating a suction effect that ensures inward resin flow and promotes tight colloidal assembly. Although the structural colors are initially faint, they intensify after water evaporation, revealing bright hexagonal close-packed structures. Precise control over particle size distribution and printing parameters enables fine-tuning of the structural colors, while segmented printing facilitates the fabrication of complex 3D microstructures with tailored color distributions and light transmission properties.

Zhongze Gu developed a printable colloidal photonic crystal ink composed of highly charged elastic nanoparticles (HENPs) dispersed in a precursor solution [65]. Using DLP, they fabricated three-dimensional colloidal photonic crystal hydrogels with customizable geometries and structural colors. In this system,

electrostatic interactions maintain the ordered arrangement of HENPs in the precursor prior to printing. During UV polymerization, this order is “locked” into the structure, yielding stable 3D objects. By modifying the ink composition—such as incorporating thermoresponsive monomers like NIPAM—or adjusting printing parameters, they successfully created bioinspired structures that exhibit temperature-dependent color shifts.

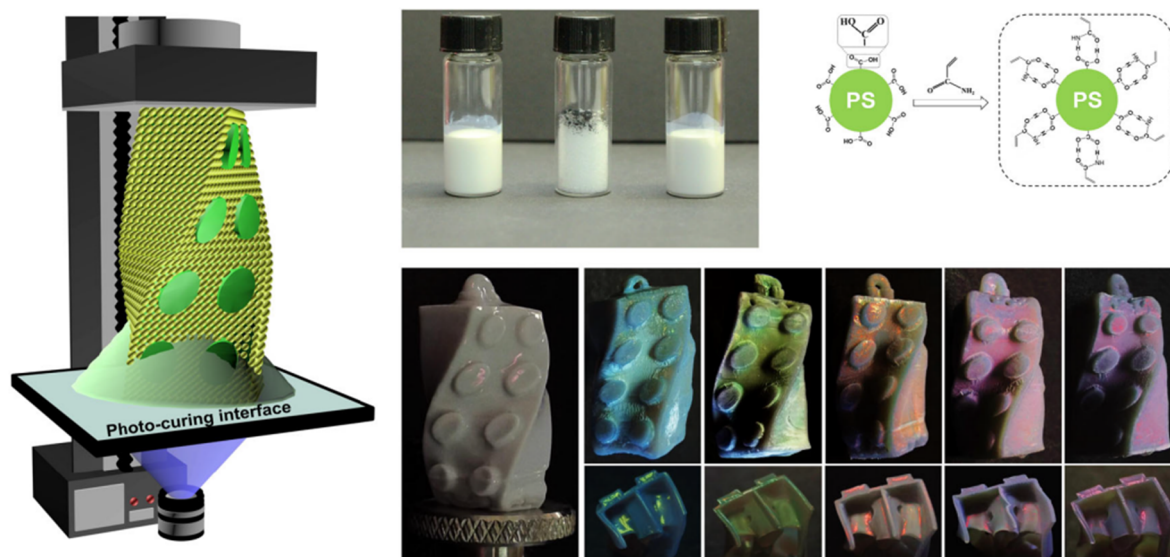


Figure 4. Schematic of hydrogen bond-induced colloidal self-assembly via DLP 3D printing. Reproduced from Ref. [63], Copyright 2022, Springer Nature.

3. Response Principles of Photonic Crystals

Responsive photonic crystals dynamically modulate photonic bandgap properties under external stimuli. Integrating stimuli-responsive materials with photonic crystal structures enables Responsive photonic crystals fabrication. To understand bandgap modulation, the coloration mechanism must first be clarified. The diffraction properties of periodic photonic crystal arrays follow the Bragg diffraction equation (Equation (20)):

$$m\lambda = 2(n_l d_l + n_h d_h) \quad (20)$$

where m is the diffraction order, n_l and n_h are refractive indices of low/high-index materials, and d_l and d_h are their respective thicknesses. For complex systems like 3D colloidal arrays, the wavelength of diffracted light is described by a modified Bragg equation (Equation (21)) [38,39,66]:

$$\lambda_{max} = 1.633 \frac{d}{m} \sqrt{\sum n_i^2 V_i - \sin^2 \theta} \quad (21)$$

where λ_{max} is the Bragg diffraction peak wavelength, d is the characteristic length of the periodic structure, m is the Bragg order; n_i and V_i are the effective refractive index and volume fraction of materials, and θ is the incident angle. These equations show that RPC wavelength modulation primarily relies on altering d or n .

4. Photonic Crystals for Radiation Dosimetry

Utilizing radiation as an external stimulus, the radiation-induced effects in polymers enable the modulation of structural colors in photonic crystals. This establishes a direct correlation between color and absorbed dose, thereby facilitating radiation detection. This section highlights various structural color dosimeters—primarily photonic crystals—that have been developed based on radiation-induced degradation, crosslinking, monomer polymerization, refractive index change and 3D printing. The radiation response range of photonic crystal dosimeters covers the range from Gy to MGy, meeting the needs of various radiation application scenarios, such as high-dose applications in industrial production (kGy to MGy), where degradation-type PEGDA dosimeters are the best choice. For low-dose clinical radiotherapy (Gy level, 0–20 Gy), cross-linked and polymer-based dosimeters are more suitable.

4.1. Degradation-Type Photonic Crystal Dosimeters

High-energy ionizing radiation induces scission of polymer backbones, leading to a reduction in molecular weight with increasing absorbed dose—a phenomenon known as radiation degradation. The decrease in molecular

weight reduces thermal stability and mechanical properties, thereby altering the material's physical structure or chemical composition. Disrupting the structure of photonic crystals through polymer radiation degradation enables the detection of ionizing radiation.

The authors' team investigated the ionizing radiation effects of inverse opal photonic crystals fabricated from poly(ethylene glycol) diacrylate (PEGDA) under a ^{60}Co - γ radiation field [67]. As shown in Figure 5a–c, the film color shifted from red to blue across the visible spectrum with increasing dose, exhibiting a linear wavelength–dose relationship over the range of 0–225 kGy. The underlying mechanism involves γ -radiation-induced peroxy radicals that trigger chain degradation of PEGDA under aerobic conditions, resulting in pore collapse and a reduction in the characteristic length of the inverse opal structure (see SEM results in Figure 5d).

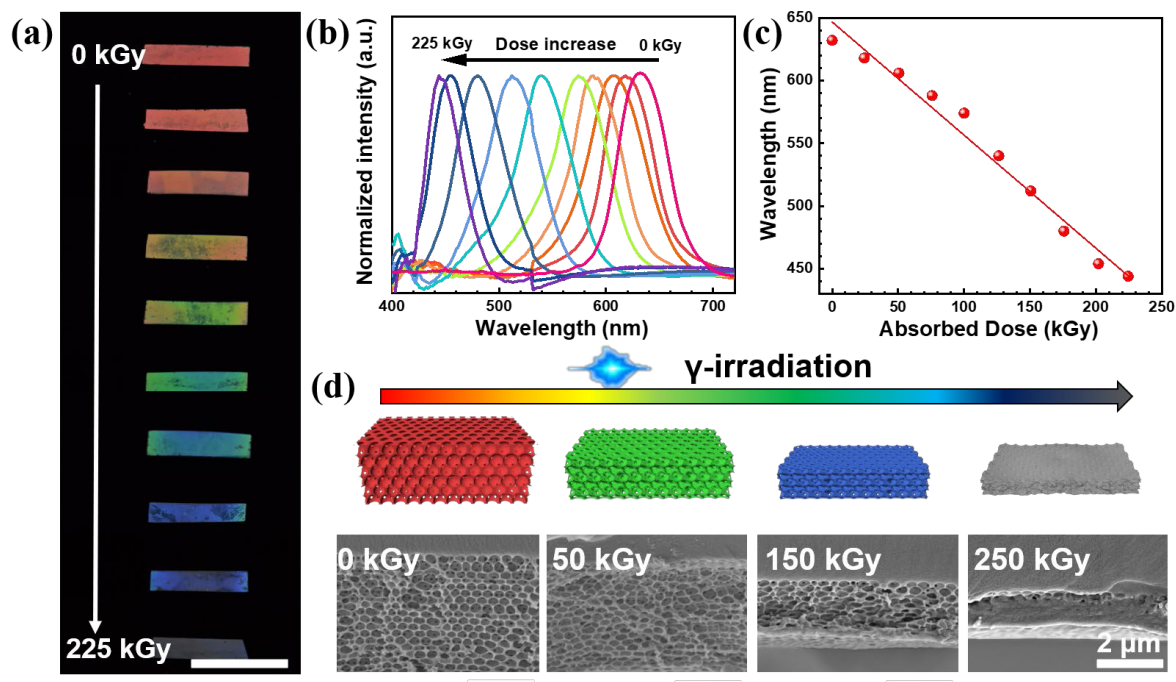


Figure 5. Radiation effects of PEGDA photonic crystals in ^{60}Co - γ field: (a) Color variation with dose; (b) Diffraction peak positions at different doses; (c) Peak shift vs. dose; (d) Schematic and SEM images of inverse opal collapse with increasing dose. Reprinted/adapted with permission from Ref. [67], Copyright 2022, Elsevier.

To modulate sensitivity, the team adjusted the molecular weight of PEGDA or incorporated non-double-bond PEG into the precursor (Figure 6) [67]. While molecular weight had minimal influence, the addition of PEG as a radiation sensitizer broadened the response range from 0–225 kGy to 0–80 kGy, yielding dosimeters with tunable sensitivity. Unirradiated samples (PEGDA film) maintained color stability for more than 62 days under ambient conditions. Notably, the films exhibited negligible changes in color or brightness after 6 h at 70 °C, demonstrating thermal stability far superior to that of commercial dosimeters for practical storage and use. However, due to the influence of post-irradiation effects, the PEGDA films after irradiation gradually shift towards the blue over time during storage, and the blue shift becomes more pronounced as the absorbed dose increases (Figure 7). Furthermore, due to the characteristic that the photonic crystal dosimeter has a continuous change in color with the absorbed dose, it has multiple reading methods, including spectrometer detection, visual comparison with color cards, and smartphone-based hue analysis, supporting applications in industrial irradiation, large-scale facilities, and medicine (Figure 8).

Subsequent studies evaluated PEGDA photonic crystal dosimeters under extreme-dose conditions and for topographic mapping [68]. Electron beam irradiation tests (dose rate: 16.2 kGy/min) revealed a distinct dose response over the range of 0–3750 kGy (Figure 9a–c). Spatial resolution studies demonstrated visible dose distributions with a two-dimensional resolution of <100 μm (Figure 9d,e), confirming the capability for ultra-high-flux electron beam measurements (~ 1 MGy). It is worth noting that the spatial resolution values reported in the work by the authors' team were measured by optical microscopy at the edge of a mask. During irradiation, a metal mask with a sharp edge was placed in close contact with the dosimeter film. After exposure, the width of the visible color transition between the irradiated and unirradiated areas was measured under an optical microscope. This method is a variation of the direct knife-edge technique, using the visible color boundary as a surrogate indicator of the dose transition. Furthermore, it can be observed in the optical microscope images that the width of the color

transition boundary is significantly smaller than those we have described (e.g., 100 μm , 30 μm , 50 μm). The reason is that when a spectrometer combined with a microscope is used to detect the reflection spectrum of the film, the minimum displacement adjustment limitation of the microscope prevents achieving higher resolution detection.

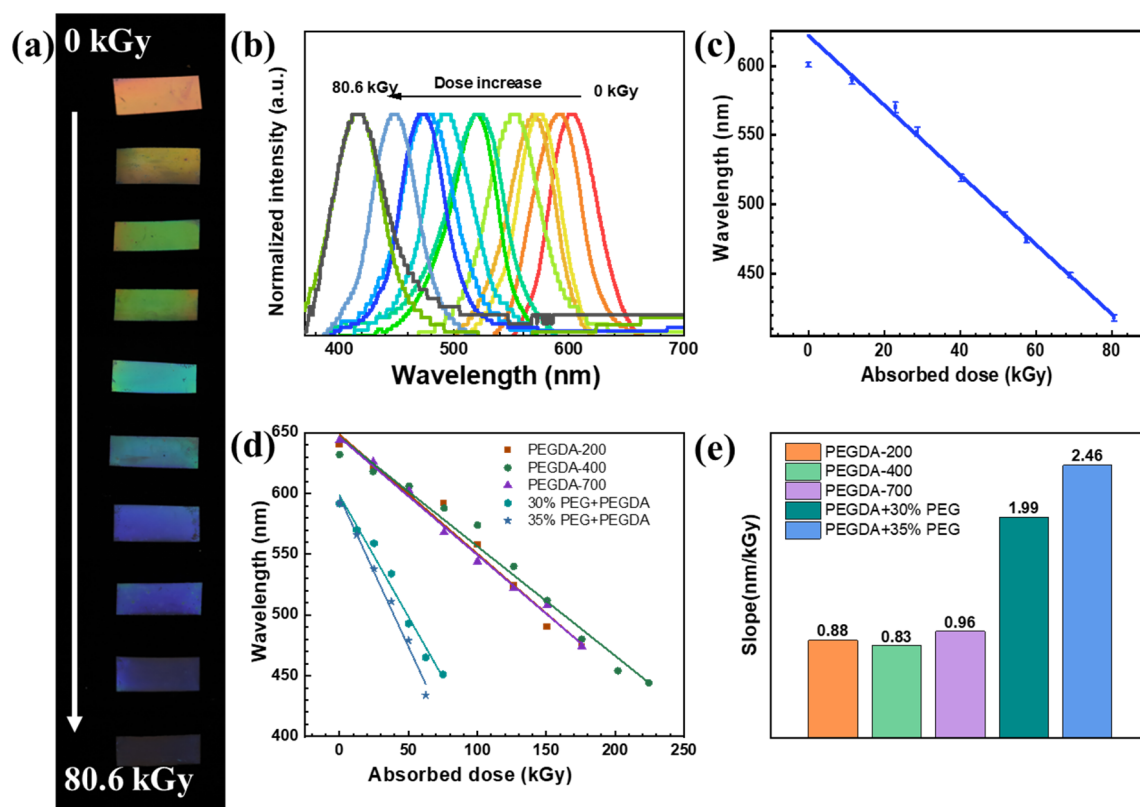


Figure 6. Radiation effects of PEG-sensitized PEGDA photonic crystals: (a) Photos of different absorption doses (30% PEG); (b) Color shift with dose (30% PEG); (c) Diffraction peaks (30% PEG); (d) Peak shifts vs. dose for varied PEGDA MW and PEG content; (e) Sensitivity profiles. Reprinted/adapted with permission from Ref. [67], Copyright 2022, Elsevier.

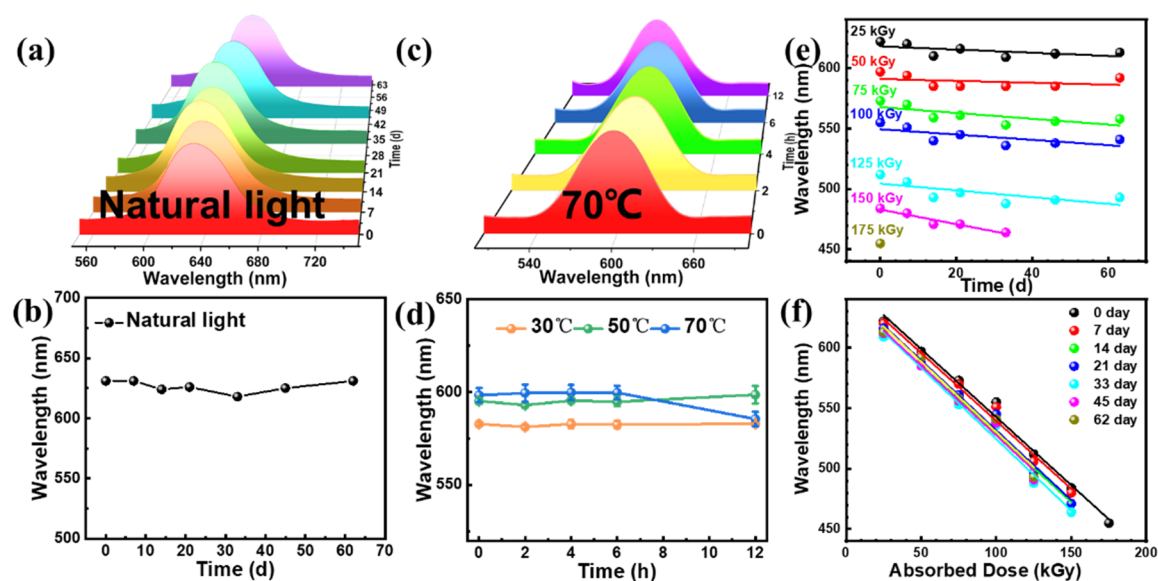


Figure 7. The long-term storage stability (a) and (b); temperature stability (c) and (d); irradiation stability (e) and (f) of the PEGDA film. (a–d) reprinted/adapted with permission from Ref. [68], Copyright 2025, John Wiley and Sons. (e–f) reprinted/adapted with permission from Ref. [67], Copyright 2022, Elsevier.

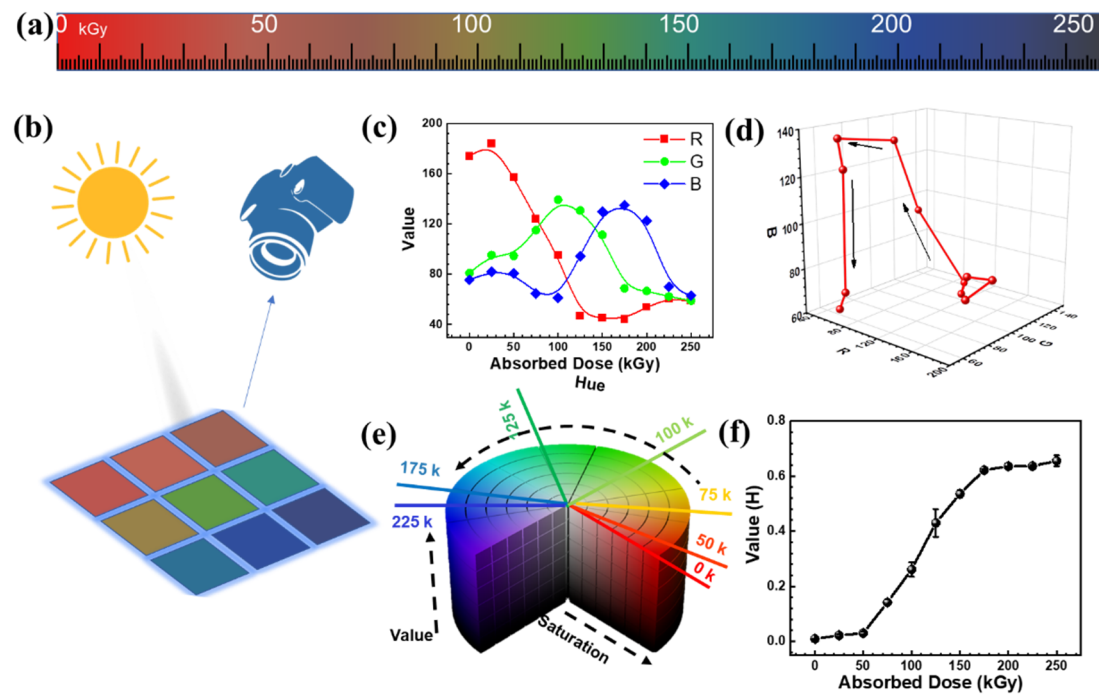


Figure 8. Reading out of doses in the absence of a spectrometer. (a) Color calibration stripe of PEGDA film at different absorbed doses. (b) Digital photo-taking and (c) RGB channel varies with absorbed dose. (d,e) Color changing of dosimeter in RGB and HSV color space. (f) Hue value of irradiated film increases with absorbed dose. Reprinted/adapted with permission from Ref. [67], Copyright 2022, Elsevier.

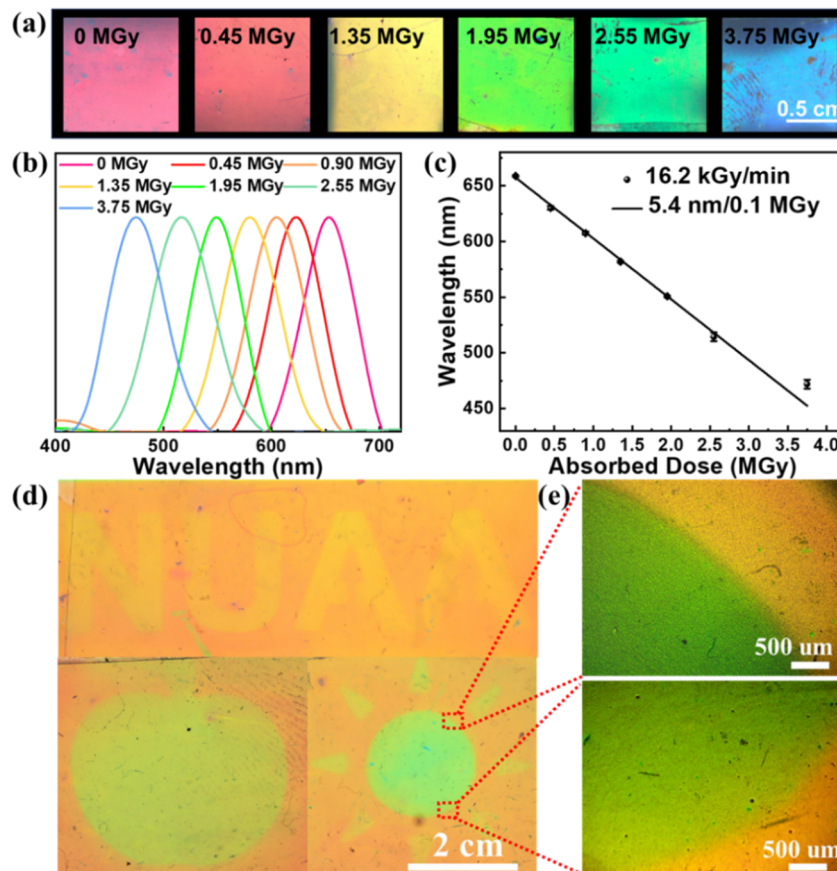


Figure 9. Electron beam response and spatial resolution: (a) Film photos; (b) Diffraction peaks; (c) Peak shift vs. dose; (d) Dose distribution under masks; (e) Optical micrograph of irradiated/unirradiated boundary. Reprinted/adapted with permission from Ref. [68], Copyright 2025, John Wiley and Sons.

Besides, Liangwen Chen further validated the proton beam response (182.5 keV, 1 mA, duty cycle 0.1, 10 Hz) of PEGDA photonic crystal dosimeters [69]. PEGDA films exhibited distinct dose-dependent color shifts and resolved proton beam profiles (~ 10 MGy), with a two-dimensional resolution of < 100 μm . This work has laid the groundwork for dosimetry applications in heavy-ion facilities, accelerator-driven systems (ADS), and heavy-ion medical treatments.

Researchers have also explored radiation-responsive structural colors beyond traditional photonic crystal structures. Hayward's group at MIT fabricated periodic polymer stacks combining a high-refractive-index P(p-MS-BP) with a low-index P(OEGMA-BP) or P(MMA-BP) [70]. These stacks exhibited bright interference colors. The P(OEGMA-BP) system underwent radiation-induced crosslinking, resulting in a blue shift upon solvent development, whereas the P(MMA-BP) system degraded, producing a red shift. Both systems responded at dose levels of approximately 100 kGy.

Liang Hu designed an interferometric film composed of hydrogel microgels (MGs) sandwiched between metal layers [71]. By incorporating radiation-cleavable disulfide, diselenide, or ditelluride bonds into crosslinked pNIPAM microgels, they enabled X-ray detection. Radiation-induced bond cleavage reduced the crosslinking density, causing the microgels to swell. This swelling increased the interlayer distance, resulting in a redshift of the reflectance spectrum. Microgels containing Se-Se or Te-Te bonds exhibited higher sensitivity (~ 100 nm/Gy) than those with S-S bonds. Unlike the GelMA gel dosimeters mentioned in Section 4.2, GelMA inverse opal photonic crystals rely on a three-dimensional periodic porous structure (air-filled pores within the hydrogel matrix). The change in structural color originates from a reduction in the characteristic lattice spacing dd (Bragg diffraction). The maximum achievable shrinkage is limited by the mechanical stiffness of the hydrogel network and the constraints imposed by the porous structure itself. Typically, the volume change of such inverse opal hydrogels is small (a few percent) even at high doses, resulting in relatively low sensitivity. In contrast, responsive microgelslayer is unconstrained in the vertical direction, it can undergo very large volume expansion (far exceeding the contraction of inverse opal networks), thereby achieving significantly higher sensitivity (by two orders of magnitude). In follow-up work [72], Liang Hu and colleagues also synthesized azobenzene (Azo)-containing microgels (Azo-MGs). Upon X-ray irradiation, ZnS converts X-rays into ultraviolet light, which then induces photoisomerization of the azobenzene groups in the microgels, leading to significant swelling of the microgel layer. This phenomenon enables reversible X-ray responsiveness and controlled drug release, providing a new strategy for applications such as precisely controllable chemoradiotherapy.

4.2. Crosslink-Type Photonic Crystal Dosimeters

Under ionizing radiation, polymers containing double-bond groups are prone to crosslinking reactions, which lead to significant changes in their physical structure or chemical properties. Utilizing the radiation crosslinking effect of polymers at low doses, in combination with photonic crystal structures, presents a promising strategy for preparing low-dose ionizing radiation-responsive photonic crystal dosimeters.

The authors' team prepared hydrogel films using gelatin methacrylate (GelMA) and reintroduced unsaturated vinyl groups through chemical modification, followed by X-ray irradiation of the hydrogel. As the vinyl groups underwent radiation-induced crosslinking, the inverse opal hydrogel experienced significant contraction, shifting its structural color from red to green, as shown in Figure 10 [67]. The results indicated that the detection sensitivity of the inverse opal hydrogel reached approximately 0.61 nm/Gy, representing a two to three orders of magnitude improvement over the previously reported PEGDA dosimeter (0.88–2.51 nm/kGy). Under X-ray irradiation, the wavelength shift exhibited a linear correlation with absorbed doses in the range of 0–60 Gy. At higher doses, crosslinking slowed due to the consumption of double bonds within the hydrogel, leading to a reduced rate of blue shift.

To verify the dosimeter's spatial resolution, the team employed a metal mask to shape the X-ray beam into a pentagram pattern for film irradiation. As shown in Figure 10e, a clear pentagram pattern appeared on the irradiated film, exhibiting high shape fidelity to the mask. Optical microscopy confirmed a sharp boundary with a transition width of less than 30 μm between irradiated and non-irradiated areas, demonstrating excellent spatial resolution. Additionally, as the irradiation depth increases, the spatial resolution of the dosimeter remains unchanged. As a natural polymer hydrogel, gelatin exhibits an effective atomic number (Z_{PEAeff}) within the photon energy range of 0.015–15 MeV. Compared to human soft tissue and water, the difference is approximately 5–12% in the low-energy region, but rapidly decreases above 0.1 MeV, and becomes less than 2% in the high-energy range of 1–15 MeV. The difference in electron density (N_{PEAeff}) between gelatin and soft tissue/water is about 3–7% above 0.1 MeV. In terms of equivalent atomic number (Z_{eq}), gelatin shows the best equivalence to breast tissue in the 1–15 MeV range, and its KERMA values in the 0.1–15 MeV range are very close to those of soft tissues (except cortical bone). For charged particles (electrons, protons, and alpha particles), gelatin exhibits excellent equivalence to

adipose tissue over the energy range of 10 keV–1 GeV, and its deviation in effective atomic number (Z_{eff}) from other soft tissues is generally less than 10%. Overall, gelatin demonstrates good tissue and water equivalence for soft tissues within the energy ranges commonly used in radiation therapy and dosimetry [73]. As the methacrylated derivative of gelatin, GelMA photonic crystals hold significant promise for use as medical hydrogel radiation dosimeters.

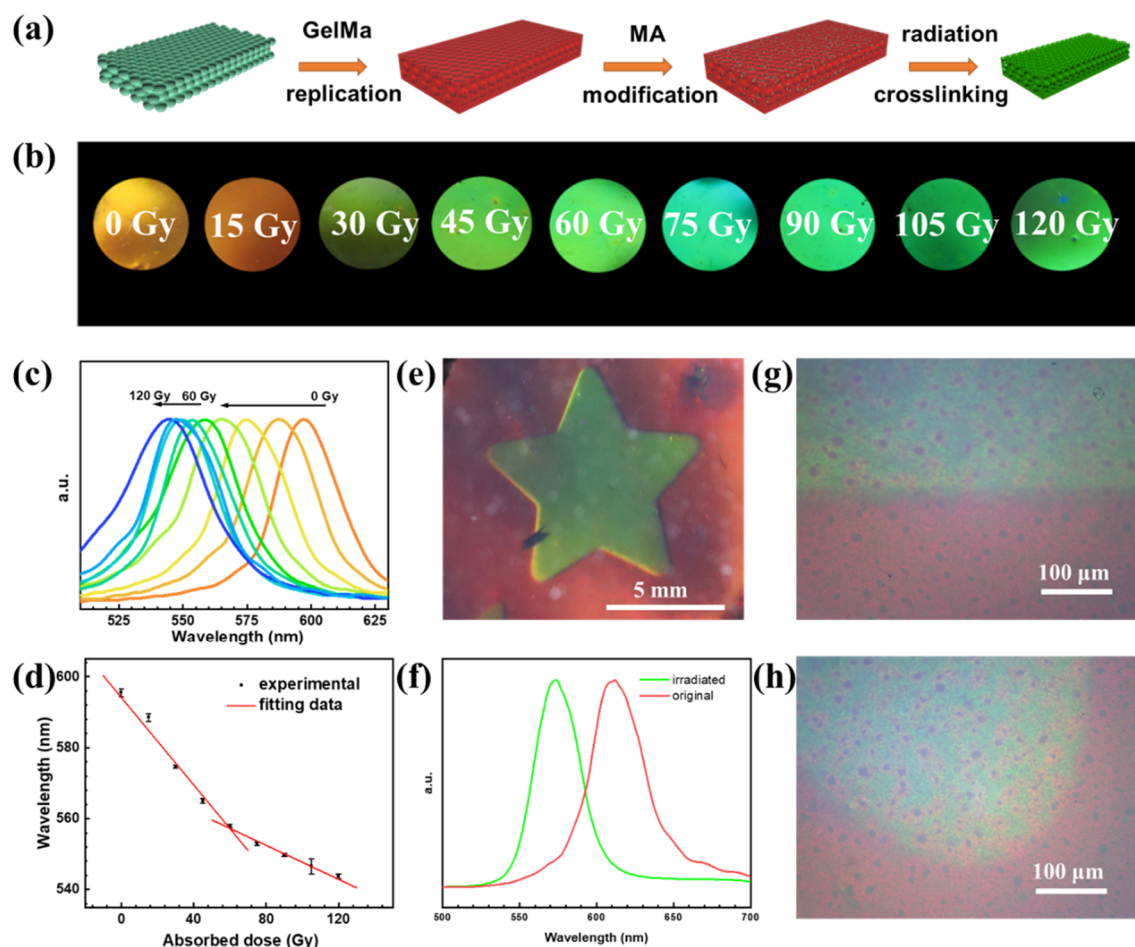


Figure 10. Fabrication and radiochromic properties of methacrylated GelMA inverse opal hydrogel films: (a) Schematic representation of the process preparing inverse opal GelMA PCs; (b and c) Digital photographs (b) and spectra (c) of methacrylated GelMA inverse opal hydrogel films irradiated with different absorbed doses; (d) Two regions linear fit of Bragg peaks wavelength obtained from (c); (e) Digital photo of methacrylated GelMA inverse opal hydrogel films irradiated in the patterned radiation field; (f) Spectra of irradiated and unirradiated areas of (e); (g and h) Enlarged areas of microscopic images of (e). Reprinted/adapted with permission from Ref. [67], Copyright 2022, Elsevier.

To further enhance radiation sensitivity, the team designed a hydrogel photonic crystal with a higher content of double bonds. Hydroxyethyl methacrylate (HEMA) was introduced during synthesis to incorporate controllable hydroxyl groups, which were subsequently modified into double bonds, yielding a series of hydrogels with tunable double-bond densities. Performance tests revealed a dramatically improved sensitivity of approximately 10 nm/Gy, enabling detection below 20 Gy and meeting the thresholds required for clinical radiotherapy [74]. The dosimeter was validated on actual radiotherapy equipment (Figure 11). Figure 11a–f present results from X-ray and electron beam accelerators, respectively, confirming linear dose responses under clinical conditions. Figure 11g–i demonstrate high consistency in spatial dose distribution compared to commercial film dosimeters. Unfortunately, for high-dose applications, color changes are visible to the naked eye; for the low-dose radiotherapy range, the color changes caused by radiation are almost impossible to distinguish with the naked eye and require the use of a spectrometer or smartphone based on hue analysis for precise quantification, while color changes still provide a rapid visual indication.

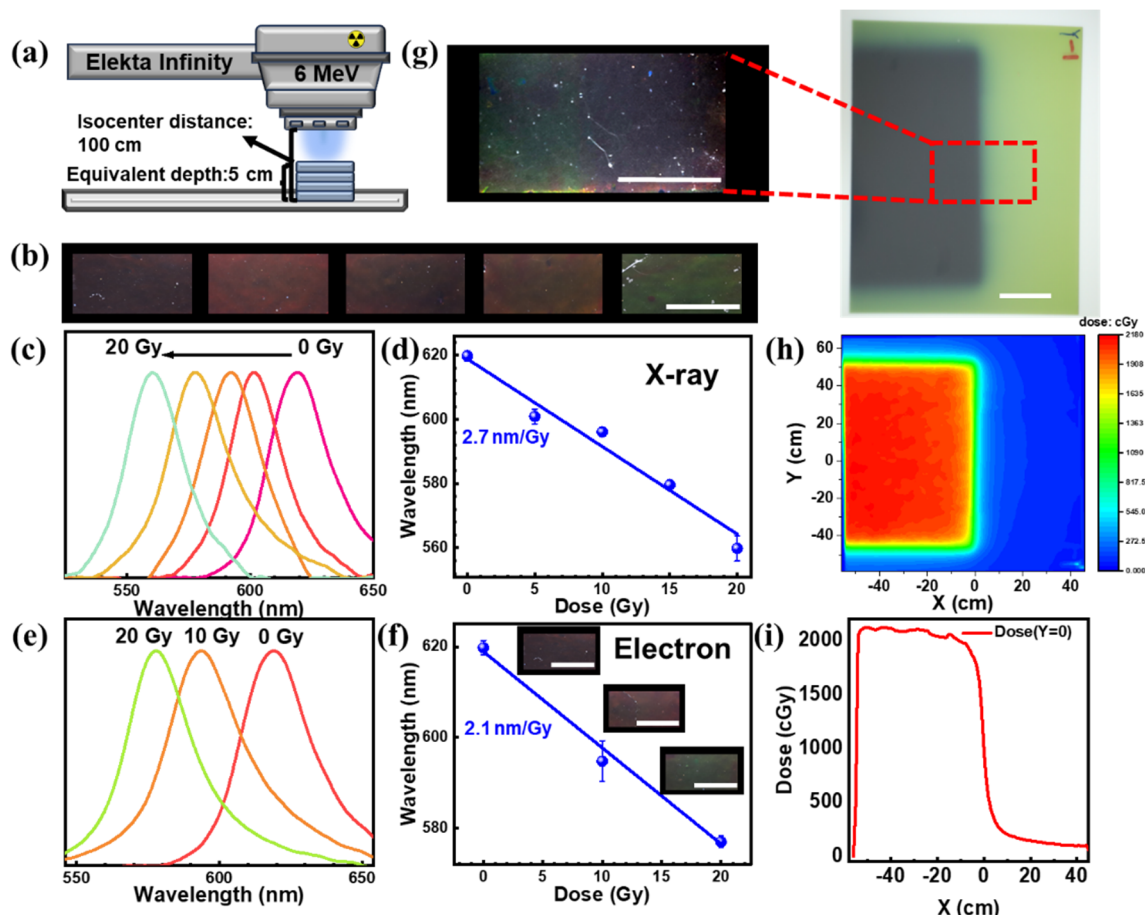


Figure 11. Response of hydrogel photonic crystal films to clinical accelerator radiation: (a) Radiation setup medical accelerator radiation; (b) digital photographs of films irradiated with an X-ray accelerator at different absorbed doses, scale bar 3 cm; (c) spectra of films irradiated with an X-ray accelerator at different absorbed doses; (d) linear fit of the Bragg peak wavelength obtained from (c); (e) spectra of films irradiated with an electron beam accelerator at different absorbed doses; (f) linear fit of the Bragg peak wavelength obtained from (e), scale bar 3 cm; (g) digital photographs of inverse opal films (scale bar 2 cm) and Cafchromict EBT3 (scale bar 3 cm) irradiated with an X-ray accelerator at 20 Gy; (h) Nephogram of Cafchromict EBT3 irradiated with an X-ray accelerator at 20 Gy; (i) dose distribution Cafchromict EBT3 irradiated with an X-ray accelerator at 20 Gy (Y = 0). Reprinted/adapted with permission from Ref. [74], Copyright 2025, Royal Society of Chemistry.

Xianlong Zhang employed magnetic fields to self-assemble Fe_3O_4 nanoparticles into photonic crystals, which were then coated with methacrylated gelatin (GelMA) to produce structurally colored GelMA hydrogel films for γ -radiation detection [75]. Upon γ -irradiation, crosslinking of the vinyl groups in GelMA induced volume shrinkage, altering the periodic structure of the $\text{Fe}_3\text{O}_4@\text{C}$ nanoparticles and triggering a color shift. The films exhibited high radiochromic sensitivity, displaying distinct green changes even at a dose of 5 Gy. This magnetic-field-assisted approach simplified the fabrication of photonic structures compared to conventional opal or inverse opal techniques. In subsequent work, Zhang Xianlong's team reported a novel X-ray-responsive photonic film. By sandwiching a magnetic-field-induced self-assembled $\text{Fe}_3\text{O}_4@\text{C}$ nanochain-GelMA hydrogel between BaF_2 scintillator plates, the film utilizes the conversion of X-rays into ultraviolet light by BaF_2 , which triggers crosslinking and contraction of GelMA, thereby reducing the interparticle spacing along the nanochain direction and producing a structural color blue shift (from orange-red to green). This film achieves a naked-eye detection threshold as low as 6 Gy, a sensitivity of 4.62 Gy^{-1} , and a linear response ($R^2 = 0.981$) within the 0–10 Gy range, providing a new strategy for real-time, visualizable, low-dose X-ray dosimetry [76].

4.3. Polymeric-Type Photonic Crystal Dosimeters

Monomers containing double bonds undergo polymerization upon exposure to ionizing radiation. Leveraging radiation-induced monomer polymerization thus represents a key strategy for developing radiation-responsive photonic crystals.

In the preparation of double-network (DN) hydrogels, radiation-induced polymerization of the secondary network monomers is commonly used to modify mechanical or swelling properties. Integrating photonic crystals into this process enables structural color changes during DN formation. The authors' team employed self-assembly of highly charged elastic nanoparticles (HENPs) to fabricate structurally colored primary-network hydrogels based on NIPAM. Under low-dose X-ray irradiation, radiation-induced polymerization of acrylamide within the gel substrate drove volume expansion, resulting in a dose-dependent red shift (Figure 12) [77]. Sensitivity was tunable by adjusting the solid content in both networks. Spatial resolution ($<50\ \mu\text{m}$) was verified using shaped masks. The resulting DN dosimeter detected X-rays in the 0–10 Gy range with a maximum sensitivity of 35.8 nm/Gy, exhibited exceptional stability against environmental factors (e.g., UV), and enabled 3D printing of complex shapes-offering new strategies for advanced radiotherapy verification. Compared with commercially available Gafchromic™ EBT3 radiochromic films, the double-network photonic crystal dosimeter exhibits comparable sensitivity in terms of dose resolution (approximately 0.5–1.0 Gy). Regarding fading (post-irradiation stability), the DN dosimeter shows an immediate color change upon irradiation and stabilizes instantly, allowing readout without any waiting time, and the dose information is unaffected by ambient light or storage duration. In contrast, EBT3 requires 16–24 h to reach a stable optical density after irradiation, during which it continues to darken. Unfortunately, the DN dosimeter has not yet been systematically characterized to verify its energy dependence and tissue equivalence. Moreover, because the DN dosimeter is a hydrogel film, it still falls short in terms of ease of preparation and use compared to EBT3.

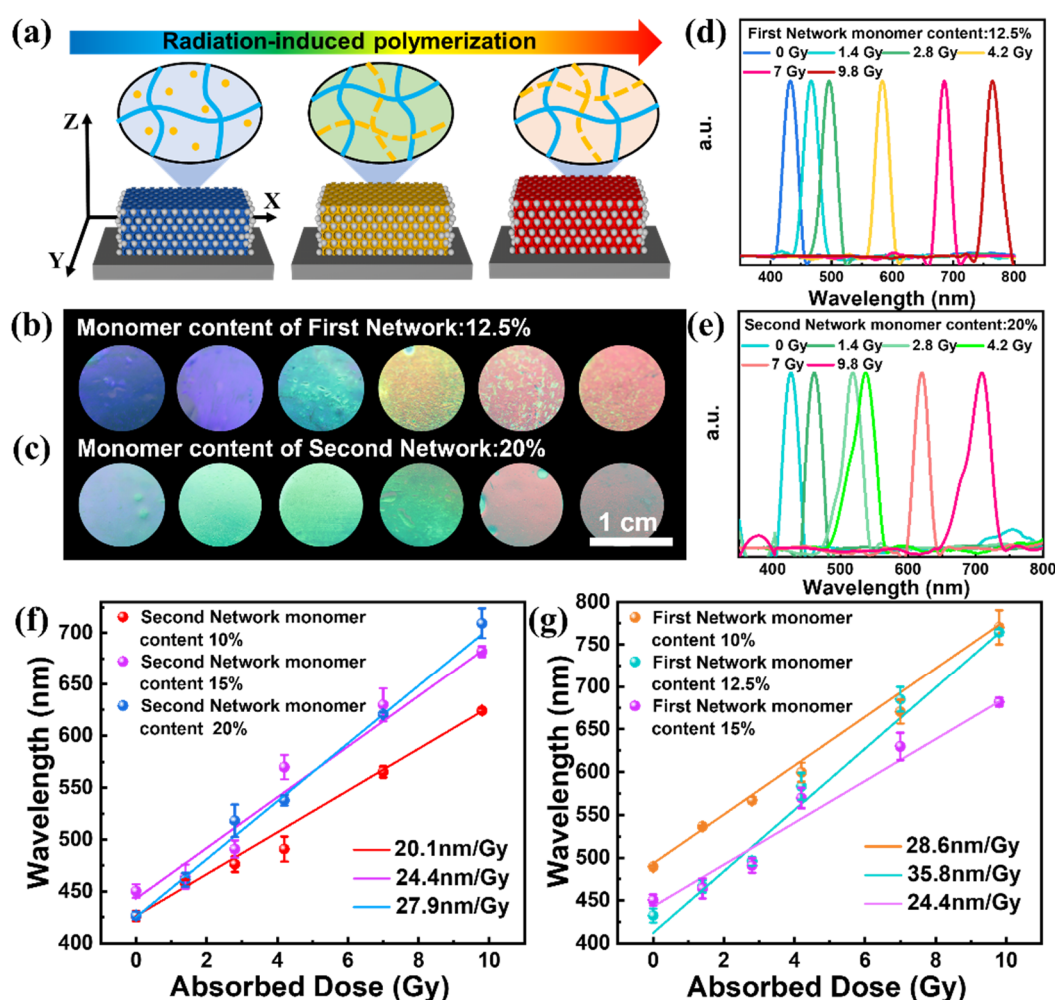


Figure 12. Double-network (DN) hydrogels dosimeter: (a) Schematic illustration of the radiation-induced structural color change in photonic crystal gel films; (b) Photographs and (d) reflectance spectra of films (first network: 12.5 wt%, second network: 15 wt%) at different absorbed dose; (c) Photographs and (e) reflectance spectra of films (first network: 15 wt%, second network: 20 wt%) at different absorbed dose; Peak wavelength shifts with different absorbed dose at (f) varying second-network monomer content and (g) varying first-network monomer content. Reprinted/adapted with permission from Ref. [77], Copyright 2026, American Chemical Society.

Besides, the team also dispersed high-concentration silica microspheres in polymerizable monomers to create liquid photonic crystal dosimeters, whose reflectance exhibited a linear response to absorbed dose [78]. The fluidity of the liquid photonic crystals allows them to conform to irregular spaces via casting, addressing the shape-adaptation limitations of conventional clinical film dosimeters and broadening their application prospects.

4.4. 3D Printing of Photonic Crystal Dosimeters

For three-dimensional dose distribution measurements, tissue-equivalent gels are clinically used to mimic human organs. In this context, precise three-dimensional hydrogel molding enables patient-specific customization. To address the challenges of detecting complex topographies in radiotherapy, the team integrated 3D printing with photonic crystals and radiation crosslinking (Figure 13). As shown in Figure 13a, structurally colored hydrogels were prepared using synthesized highly charged elastic nanoparticles (HENPs), with color tunable by adjusting the HENP concentration. Scanning electron microscopy confirmed ordered microsphere stacking, confirming the formation of photonic crystals. After methacrylation, the material exhibited high radiation sensitivity ($>30\ \mu\text{m}$ resolution) and the capability to detect complex three-dimensional topographies. Upon irradiation, a 3D-printed lotus model underwent a color shift from red to green (Figure 13b). Partial-shielding irradiation of various shapes (Figure 13c) revealed visible color differences between irradiated and non-irradiated regions, demonstrating the feasibility of this approach for complex radiation fields. The sensitivity was determined to be $0.5\ \text{nm/Gy}$ in the $0\text{--}60\ \text{Gy}$ range and $0.13\ \text{nm/Gy}$ in the $60\text{--}110\ \text{Gy}$ range.

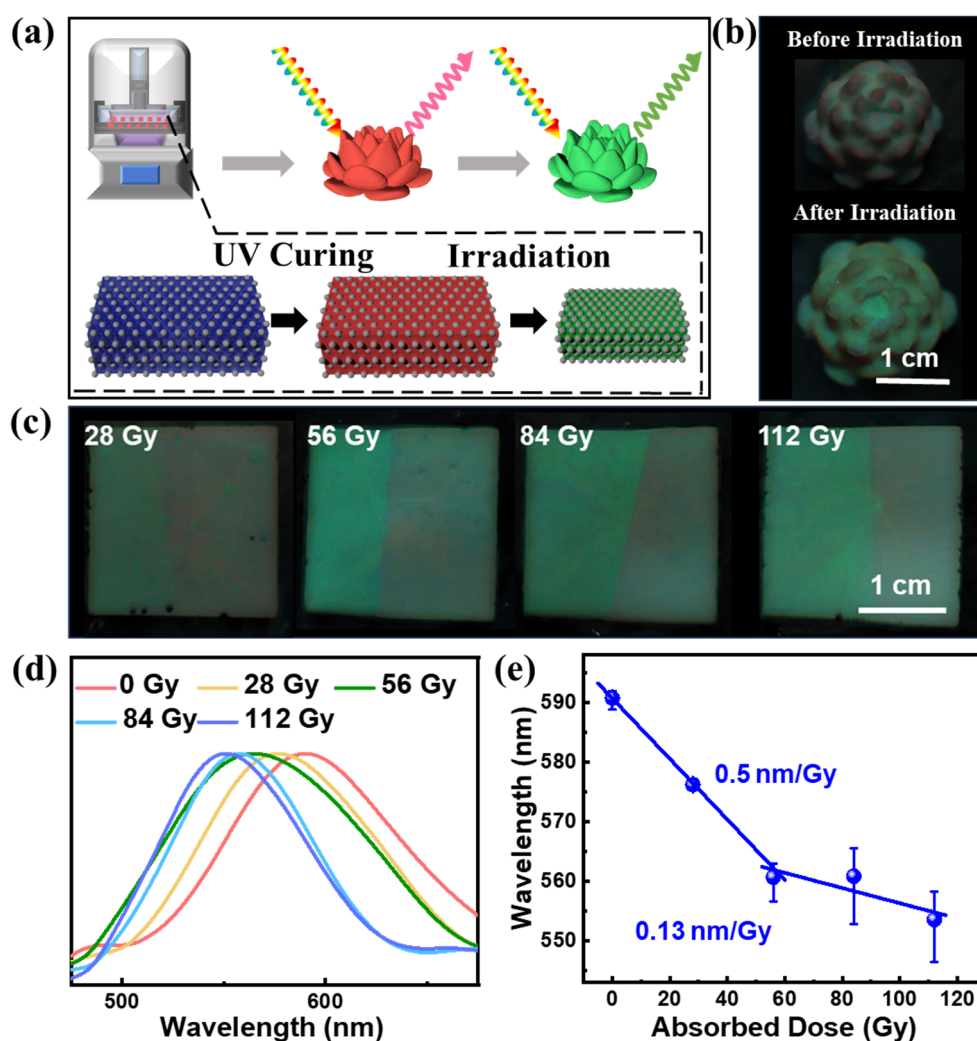


Figure 13. Fabrication and application of a 3D hydrogel radiation dosimeter: (a) 3D printing diagram; (b) 3D printing lotus model before and after irradiation; (c) 3D printed cube models with different doses of radiation; (d) spectra of 3D printed cube models with different doses; (e) linear fit of the Bragg peak wavelength obtained from (d). Reprinted/adapted with permission from Ref. [74], Copyright 2025, Royal Society of Chemistry.

Subsequently, combining radiation-induced polymerization with 3D printing further enhanced sensitivity (Figure 14). In contrast to crosslinking-based dosimeters, the double-network (DN) dosimeters expanded with increasing dose, resulting in a red shift. Figure 14c shows a square hydrogel block half-shielded by lead: the unirradiated side remained green, while the irradiated side progressively turned red. The diffraction peaks exhibited a dose-dependent red shift (Figure 14d), with sensitivities of 6.7 nm/Gy in the 0–10 Gy range and 2.1 nm/Gy in the 10–25 Gy range (Figure 14e) values higher than those of crosslinked 3D dosimeters.

Using flower-shaped masks (Figure 14f), sharp boundaries between the irradiated and non-irradiated regions confirmed the spatial resolution. Rapid readout, low-dose response, high resolution, and environmental stability highlight the potential of this approach for clinical topographic dose mapping.

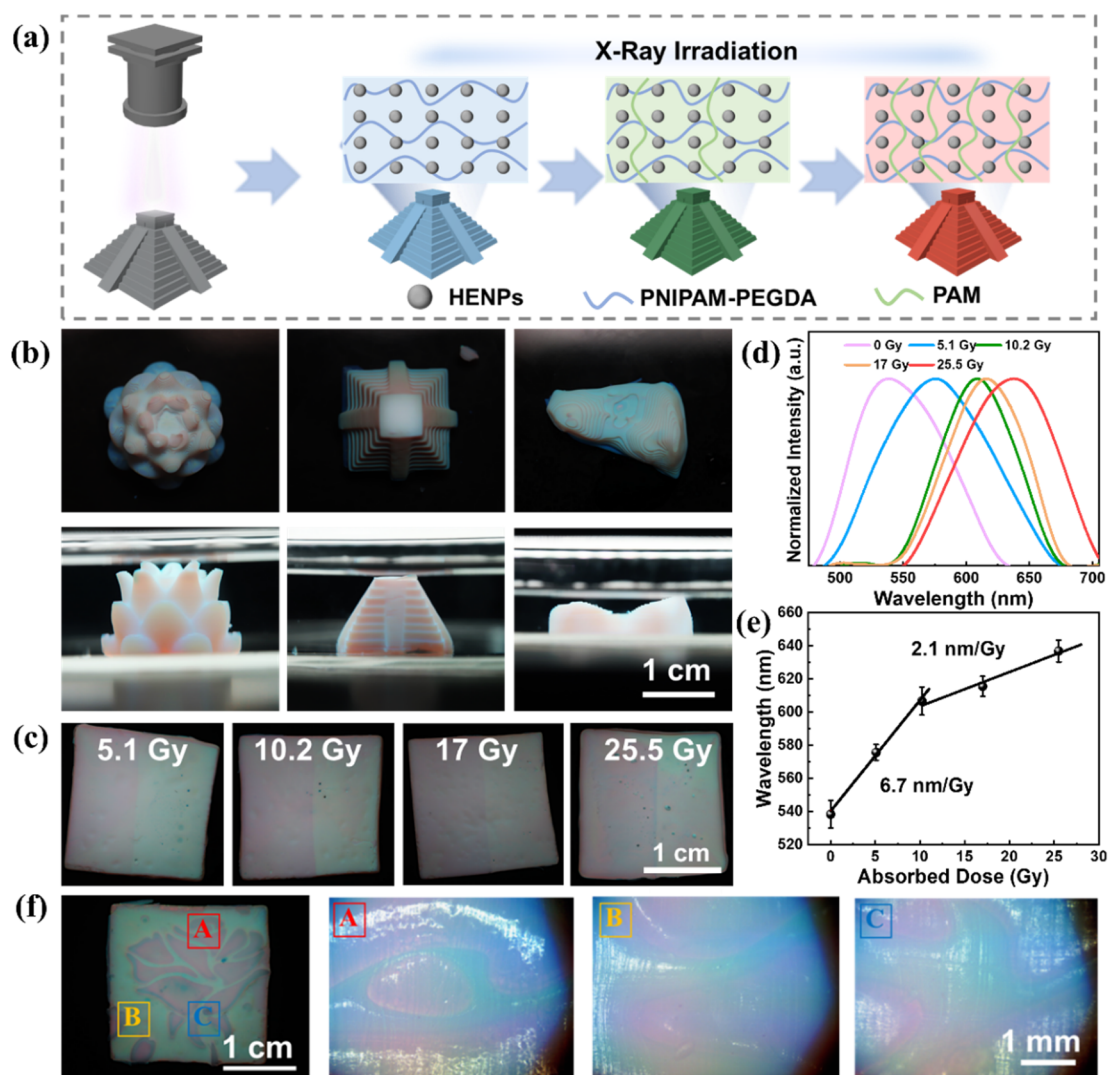


Figure 14. 3D double-network hydrogels dosimeter: (a) Schematic of 3D printing and radiation-induced color change in photonic crystal hydrogel dosimeters; (b) Photographs of representative 3D-printed hydrogel models (lotus, pyramid, liver); (c) Photographs of 3D printing models with different absorption doses; (d) Spectra of 3D printing models with different absorption doses; (e) Changes in spectral diffraction peaks of 3D printing models with respect to absorption dose; (f) Verification of spatial resolution capability of 3D printing dosimeter. Reprinted/adapted with permission from Ref. [77]. Copyright 2026, American Chemical Society.

4.5. Refractive Index Change Types Photonic Crystal Dosimeters

In addition to the responsive photonic crystal dosimeters based on radiation-induced degradation, crosslinking, and monomer polymerization described above, researchers have recently explored novel photonic crystal structures and detection principles that rely primarily on radiation-induced changes in the refractive index of materials rather than structural deformation. By modulating photonic bandgaps or resonant modes through refractive index variation, these designs exhibit unique advantages in sensitivity, detection range, integrability, and application scenarios.

Hameed team designed a square-lattice silicon pillar array (lattice constant 200 nm, pillar radius 45 nm) with a central silicon ring cavity (diameter 500 nm, thickness 88 nm). The cavity was filled with a polyvinyl alcohol (PVA) polymer doped with crystal violet and fuchsin dyes. Gamma irradiation changes the refractive index of the polymer, causing a shift in the transmission resonance peak; the absorbed dose is determined by measuring the wavelength shift. This structure achieves a sensitivity of 150 nm/RIU, a quality factor (Q) of 808, a detection limit of 10^{-4} RIU, and good linearity in the range of 0–70 Gy. This work offers high sensitivity and good repeatability, but with complex fabrication process (requiring electron-beam lithography, etc.), sensitivity to the polarization of incident light, and a limited low-dose range that is difficult to extend to high-dose scenarios [79].

Elsaket proposed a dual-core photonic crystal fiber (PCF) dosimeter based on the surface plasmon resonance (SPR) effect [80]. The structure consists of a hexagonal array of air holes in a PCF; the top two rows of air holes are enlarged and polished to form a D-shaped planar surface, onto which a TiO_2 layer (to enhance gold adhesion) and a gold layer (thickness 50–200 nm) are sequentially coated. Upon gamma irradiation, the refractive index of PVA changes, causing a shift in the SPR loss peak wavelength. This fiber-optic sensor exhibits a sensitivity of 6 nm/Gy, enables remote real-time detection, and is suitable for strong radiation environments such as nuclear reactors. It offers advantages such as small size, electromagnetic immunity, and convenient remote measurement. However, the dosimeter has a relatively low sensitivity, and the metal layer may oxidize or peel off under high doses; its long-term stability requires further verification.

Bradley team focused on the thermoluminescence (TL) dosimetric properties of Ge-doped photonic crystal fibers [81,82]. They fabricated Ge-doped silica preforms using modified chemical vapor deposition, drew the preforms into PCFs via the stack-and-draw method, and then fully collapsed the air-hole array at high temperature to form solid fibers (collapsed PCFs). Gamma irradiation creates defect energy levels in the fiber, storing energy; upon heating, electrons are released and recombine, emitting a TL signal whose intensity is proportional to the absorbed dose. The collapsed PCFs exhibit a TL response reaching 94% of that of commercial TLD-100, with a minimum detectable dose of 0.6 mGy and a linear range of 0.5–8 Gy. The advantages include high sensitivity, batch fabrication, and low cost. However, similar to conventional thermoluminescent dosimeters, this dosimeter requires thermal readout (cannot be used for real-time monitoring), the signal is erased after readout (non-reusable), and the TL signal is affected by the heating rate and ambient temperature.

The team from Beni-Suef University in Egypt systematically investigated a series of gamma dosimeters based on one-dimensional photonic crystals, covering various structural designs, including 1D alternating layers of porous silicon and polymer (porous silicon porosity 20–85%, filled with PVA and dye); ring-shaped photonic crystals (SiO_2 core surrounded by 40 bilayers); Thue-Morse quasiperiodic structures (alternating Al_2O_3 and poly(ethylene oxide) nanocomposites, Figure 15); 1D structures with a GaAs defect layer (porous silicon filled with chalcogenide glass $\text{Se}_{70}\text{S}_{30-x}\text{Sb}_x$); topological edge-state symmetric structures (silicon-doped poly(ethylene oxide)); and nano-textured interface 1D photonic crystals (PMMA nanocomposite layers) [83–89]. Detection is achieved by monitoring the wavelength shift of the photonic bandgap edge or defect modes, with sensitivities ranging from 0.15 nm/Gy to 4717 nm/RIU and Q factors as high as 1.33 million. These structures offer design flexibility, tunable performance, and coverage of a wide dose range. However, some structures are sensitive to the incident angle, the fabrication of quasiperiodic and textured interfaces is challenging, and they are susceptible to temperature interference.

Finally, Entezar introduced topological photonic crystals and Tamm resonance into gamma dose detection [90,91]. For the topological structure, they constructed an interface between two 1D photonic crystals of the form $(\text{ABA})^{10}$ and $(\text{B}'\text{A}'\text{B}')^{10}$ (where A/A' are porous silicon layers with different porosities filled with PVA + dye, and B/B' are porous silicon layers filled with the same polymer), exciting a topological edge state. For the Tamm structure, they designed a metal (Ag)/porous silicon photonic crystal interface (the porous silicon again filled with PVA + dye) to excite a Tamm resonance. Both configurations operate at normal incidence without requiring prism coupling. Gamma irradiation changes the refractive index of the polymer, causing a shift in the resonance peak of the edge state or Tamm state. The topological structure yields a sensitivity of 0.22 nm/Gy, a Q factor of 9734, and a detection limit of 0.013 Gy; the Tamm structure gives a sensitivity of 0.149 nm/Gy and a Q factor of 761. These structures are compact, can operate at normal incidence, are resistant to fabrication defects, and are easy to integrate. However, their sensitivity is relatively low (one to two orders of magnitude lower than that of one-dimensional defect-mode structures), and the metal layer may introduce additional losses.

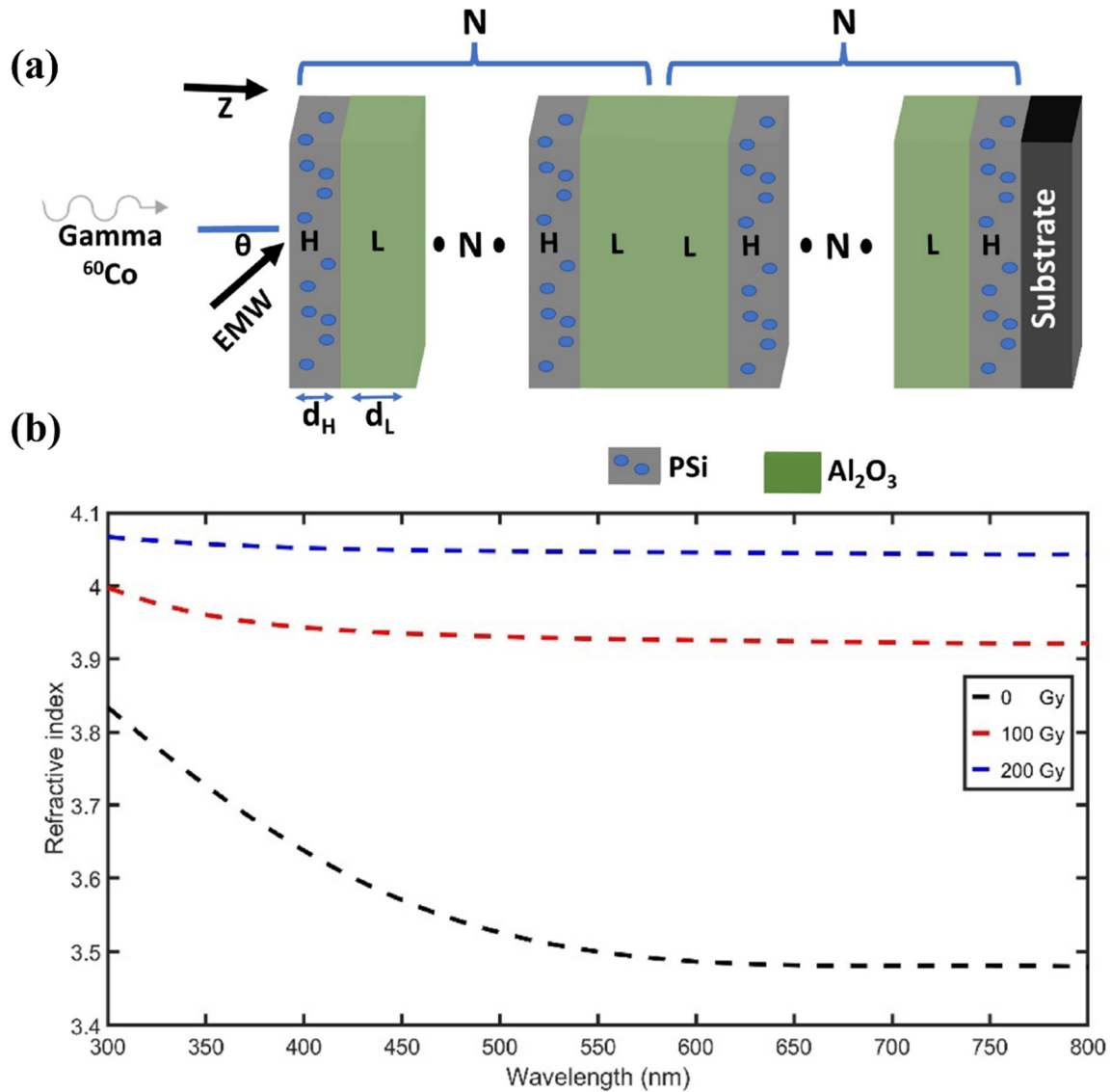


Figure 15. (a) Schematic design of symmetrical PhCs composed of silicon doped with PEONC; (b) Is of PSi (P = 10%) doped with PEONC at different gamma doses from 0 to 200 Gy. Reproduced from Ref. [88], Copyright 2025, MDPI.

4.6. Comparison of Parameters of Various Types of Dosimeters

To facilitate a comprehensive comparison of the diverse photonic crystal dosimeters discussed in the preceding sections, we summarize their key performance parameters in Tables 1–3. Table 1 compares the material and type, radiation type, dose range, sensitivity, spatial resolution, advantages, and limitations of each dosimeter type. Table 2 further evaluates dose-rate dependence, energy dependence, angular dependence, linear range, precision/accuracy, and post-irradiation fading (storage stability). Table 3 highlights the overall advantages of photonic crystal dosimeters over conventional dosimeters in terms of readout procedure, readout time, environmental stability, spatial resolution, visual dose indication, equipment dependence, and fading behavior. These tables are compiled from the experimental data and literature cited in the main text, providing a quick reference for selecting appropriate dosimeters for specific applications.

Table 1. Comparison of materials, radiation types, dose ranges, sensitivity (nm/Gy), spatial resolution, advantages and limitations of different types of photonic crystal dosimeters.

Materials and Type	Radiation Type	Dose Range	Sensitivity	Spatial Resolution	Advantages	Limitations
PEGDA [67–69] (Degradation-type)	γ -ray/electron beam/proton beam	γ : 0–225 kGy/ e-beam: 0–3250 kGy/ proton beam: 0–1.76 MGy	γ : 0.00083 nm/Gy e-beam: 0.054 nm/Gy	<100 μ m	Naked-eye readable, pre/post stability, multiple readout methods	High-dose range, fabrication relatively complex
PNIPAM with S-S, Se-Se or Te-T bond [71,72] (Degradation-type)	X-ray	0–50 Gy	~100 nm/Gy	Not specified	Reversible, high sensitivity, potential for drug release	fabrication relatively complex
Polymeric [70] (Degradation-type)	γ -ray	0 – 400 kGy	Not specified	Not specified	bright interference colors	Relatively high dose (~100 kGy), lower sensitivity
GelMA [67] (Crosslinking-type)	X-ray	0–120 Gy	0.61 nm/Gy	<30 μ m	Tissue-equivalent, stackable for 3D detection	complex double-bond modification, limited double-bond content
AM/HEMA/PEGDA [74] (Crosslinking-type)	X-ray/electron beam	0–21 Gy	10 nm/Gy		higher sensitivity, tunable range, good stability, immediate readout	Complex modification, energy dependence
BaF ₂ + Fe ₃ O ₄ /GelMA [76] (Crosslinking-type)	X-ray	0–10 Gy	4.62 nm/Gy	Not specified	Scintillator converts X-rays to UV, triggers GelMA crosslinking blue shift, naked-eye visible	fabrication relatively complex
NIPAM+PEGDA+HENPs [77] (Polymerization-type)	X-ray	0–14 Gy	35.9 nm/Gy	<50 μ m	Simplified fabrication, high sensitivity, good environmental stability	Temperature-sensitive at low doses, needs XY constraint,
Dual-core PCF-SPR [80] (refractive index type)	γ -ray	0–70 Gy	6 nm/Gy	Not specified	Remote real-time detection, immune to electromagnetic interference	Metal layer may oxidize/peel, long-term stability questionable
PVA+dye [83–89] (refractive index type)	γ -ray	0–70 Gy	0.15 nm/Gy	Not specified	Flexible design, tunable performance, wide dose range	angle-sensitive, difficult fabrication, temperature interference

Table 2. Comparison of Dose Rate Dependence, Energy Dependence, Angular Dependence, Linear Range, Precision/Accuracy and Fading (Post-Irradiation Stability) of different types of photonic crystal dosimeters.

Dosimeter Type	Dose Rate Dependence	Energy Dependence	Angular Dependence	Linear Range	Precision/Accuracy	Fading (Post-Irradiation Stability)
PEGDA [67–69] (Degradation-type)	Yes (sensitivity decrease with dose rate increase)	—	Normal incidence used (structural color angle-dependent)	γ : 0–225 kGy; e-beam: 0–3250 kGy	—	Yes (Post-irradiation effect (continued blue shift))
AM/HEMA/PEGDA [74] (Crosslinking-type)	Yes (sensitivity lower at radiotherapy dose rate)	Different sensitivity for low-energy X-ray vs. 6 MeV beams	—	0–10 Gy	—	Excellent (spectra unchanged for 11 months in fridge)
BaF ₂ + Fe ₃ O ₄ /GelMA [76] (Crosslinking-type)	—	Yes (scintillator-dependent)	—	0–10 Gy (linear)	Naked-eye threshold 6 Gy	No
Polymerization-type (double network)	—	—	—	0–14 Gy (linear)	—	Good (10 dry-wet cycles stable, UV 12 h stable)
2D Si PhC [79] (refractive index type)	—	—	Polarization sensitive (TE mode)	0–70 Gy	Quality Factor Q = 808	—
Dual-core PCF-SPR [80] (refractive index type)	—	—	Fixed angle (SPR)	0–70 Gy	—	Metal layer oxidation may affect long-term stability
PVA+dye [83–89] (refractive index type)	—	—	1D-PhC angle-sensitive	0–70 Gy	High Q suggests good precision	—

Table 3. The advantages of photonic crystal dosimeters over traditional dosimeters.

Parameter	Conventional Dosimeters (TLD, Film and Gel)	Photonic Crystal Dosimeters
Readout procedure	TLD: heating required; Film: 24 h wait; Gel: MRI/CT needed	Naked-eye observation of structural color change; immediate readout by spectrometer or smartphone HSV analysis
Readout time	TLD/gel require post-processing; film has 24 h delay	Immediate readout after irradiation—no waiting
Environmental stability	Films sensitive to UV/temperature/humidity; TLD sensitive to ambient temperature	Stable for 62 days at room temperature, 6 h at 70 °C
Spatial resolution	Film ~100 µm; gels limited by diffusion	30~100 µm
Visual dose indication	Requires instrument conversion (OD, counts, etc.)	Naked-eye visible continuous color change (red→green→blue or red shift)
Equipment dependence	Needs specialized readers (TL reader, densitometer, electrometer, MRI)	Only a visible-light spectrometer or a smartphone (or even a color-matching card) is needed
Fading (Post-Irradiation Stability)	information cannot be saved for a long time and is susceptible to the influence of environmental factors such as ultraviolet light and temperature.	Spectra unchanged for 11 months in fridge

5. Summary and Outlook

Although the integration of photonic crystals with polymer radiation effects offers significant promise for developing dosimeters with advantages such as naked-eye readability, tunable response ranges, environmental stability, high spatial resolution, and 3D printability—demonstrating great potential for radiation detection and field mapping—further research is needed in the following areas.

5.1. Expansion to Neutron, Heavy Ion, and Other Radiation Types

Current studies have mainly focused on γ -rays, electron beams, proton beams, and X-rays. Future efforts should expand to neutrons, heavy ions, and other radiation types. For neutron-sensitive photonic crystals, the following material properties are desirable: (i) incorporation of neutron capture elements such as ^{10}B , ^6Li , or Gd into the photonic crystal structure (e.g., as dopants in colloidal particles or as functional groups in the polymer matrix), where neutron capture produces charged particles that induce crosslinking or degradation; (ii) high stopping power for secondary charged particles (e.g., α particles, tritons, or conversion electrons) to ensure efficient energy transfer to the responsive polymer network. Preliminary designs could use boron-containing materials (e.g., boric acid, phenylboronic acid, phenylboronate esters, etc.) incorporated into the polymer matrix or assembled into photonic crystal structures. For heavy ion detection, the focus should be on linear energy transfer (LET) dependence, which may require tuning the sensitivity via double network or crosslink density to achieve dose-averaged LET measurements.

5.2. Improving Storage Stability of Hydrogel-Based Low-Dose Dosimeters

Hydrogel-based dosimeters (e.g., crosslinking type and double network types) currently face challenges in long-term storage due to water evaporation and potential microbial growth. The following strategies can improve shelf life and storage stability: (i) use of non-hydrogel alternatives such as organogels (e.g., PEG-based or gelatin-free formulations) that retain structural color without water; (ii) incorporation of humectants (e.g., glycerol, trehalose) to reduce water loss and maintain swelling equilibrium; (iii) encapsulation with gas- and water-impermeable films (e.g., laminated PET/PP or aluminum-coated pouches) to prevent dehydration and oxygen ingress; (iv) addition of antimicrobial agents (e.g., silver nanoparticles or sodium azide) to prevent mold growth during extended storage. Furthermore, for practical deployment, ready-to-use dry films that can be hydrated just before irradiation are a promising direction.

5.3. Clinical Translation

Current research on photonic crystal dosimeters is still at the laboratory exploration stage, and there remains a significant gap before clinical translation. Future efforts must adopt more rigorous standards for evaluation, including: (i) large-scale reproducibility—establishing batch-to-batch consistency in sensitivity, dose range, and spatial resolution under good manufacturing practices (GMP); (ii) pre-clinical validation—performing systematic tests using clinical linear accelerators (Elekta, Varian, etc.) across multiple centers to assess inter-operator and inter-machine variability, including dose rate, energy, and field size dependencies; (iii) comparison with gold standards—benchmarking against commercial dosimeters (e.g., GafChromicTM EBT3 films, ionization chambers, and MRI-based gel dosimeters) for both 2D and 3D dose verification; (iv) establishment of readout protocols—developing standardized procedures for spectral measurement, color card matching, or smartphone-based hue

analysis that are simple, fast, and user-independent; (v) validation of safety (materials must be non-toxic and non-sensitizing), performance (accuracy, intrinsic spatial resolution, linearity, fading, and environmental stability), and clinical utility (e.g., ease of use in a radiotherapy department). Clinical trials would be needed to demonstrate equivalence or superiority to existing dosimeters; (vi) commercialization—partnering with medical physics companies or dosimetry service providers to integrate photonic crystal films into existing quality assurance workflows.

Author Contributions

Z.W.: writing—original draft, writing—review & editing; Q.X.: writing—review & editing; L.Y.: writing—review & editing; P.W.: writing—review & editing; B.L.: writing—review & editing; Y.A.: supervision, writing—review & editing; J.M.: supervision, writing—review & editing. All authors have read and agreed to the published version of the manuscript.

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Informed Consent Statement

Not applicable.

Data Availability Statement

This study is a systematic review; no new datasets were generated or analyzed. All data supporting the findings are derived from previously published articles, as cited in the manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

Use of AI and AI-Assisted Technologies

During the preparation of this work, the authors used DeepSeek to polish the text. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

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